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Abstract

The US military has come to rely on global positioning system (GPS) position, navigation, and timing (PNT) and radio frequency (RF) communications to a fault. While such capability provides a robust flexibility and tight decision making cycles, the reliance upon it presents critical vulnerabilities. The recent growth of the anti-access, area denial (A2AD) concept, along with anti-satellite (ASAT) capabilities and other aspect of contested and congested environments portends a future that requires more secure communications means, with increased capacity. Free space optical (FSO) laser communications (LC) systems, especially when used in a hybrid fashion with RF capabilities, offers increased security, increased data rate (read bandwidth), longer range, and reduced dependency on GPS and satellite communications (SATCOM). To meet these challenges, this paper recommends the accelerated development of next generation inertial navigation unit (INU) and clock technology, FSO LC aperture development, requirements for hybrid communications capabilities on current and future platforms, and development of a high altitude, long duration, multi-role communications and intelligence, surveillance, and reconnaissance (ISR) platform.

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Introduction

The United States has enjoyed several benefits inherent to the unipolar world over the past quarter century. Though far from the largest in the world, the current US military is arguably the most capable and wields some of the most advanced technology and engineering. One of the many strengths that underpins the aggregate military capability—and is indeed a hallmark of the American way of war—is the capability to command, control, and communicate (C3). From the rudimentary radio relays that General Elwood "Pete" Quesada engineered between ground forces and close air support (CAS) in the North African campaign of World War II,[1] to the several data links (Joint Tactical Information Distribution System [JTIDS], Link 16, etc) that have benefited the most recent decades, to the robust and elaborate systems and networks that undergird today's Combat Air Operations Centers (CAOCs), the capability and capacity to communicate via voice and share data represents the linchpin of critical decision-making in real time.

Modern C3 permits the coordination of multiple platforms, units, formations, and echelons across a broad spectrum. Even more than this coordination, though, and at the root of the issue is the decision-making cycle and the inherent flexibility that a robust C3 capability delivers. In a complex world where combat moves faster and farther than ever before, the ability to tighten decision cycles and adapt to rapidly changing situations will likely determine the victor. The latency of simply reporting information at a mission's conclusion is insufficient in modern combat—transmitting data and sharing a common operating picture (COP) in real time has proven critical for time sensitive targeting (TST) and other mission sets.

While command, control, and communications represent a core strength of the US military, those capabilities also present vulnerabilities. Rather than fight the United States tête-à-

tête at the "high end" of combat, prospective adversaries will likely apply indirect methods to slow decision cycles, detract from flexibility, and impede mission success. Indeed, such challenges are deeper and wider in the A2/AD battlespace which is growing ever more complex. More than just a physical, kinetic deterrent, the concept of creating a contested environment stretches across all domains, including cyber and space. Radio frequencies (RF) can be jammed, denied, intercepted, exploited, or spoofed, threatening everything from voice communications to data links. Precise position, navigation, and timing (PNT) via global positioning systems (GPS) can be degraded or denied by jamming aircraft platforms and weapons guidance kits, or worse yet, by neutralizing some or all of the GPS constellation that supports military operations.

Rather than merely continue the development of frequency-hopping and encryption techniques to insulate RF communications (both voice and data) against the current and emerging technological threats, free space optical (FSO) laser communications (LC) offer a new medium of communicating with enhanced security, greater range, and higher data rates. Lasers communicate by sending bursts or pulses directly to the intended recipient instead of widely propagating a radio wave. Thanks to the "directed" nature of the signal, the communications would be near impossible to intercept, with the added benefit of higher data rates, and increased range. This would also help mitigate or solve the capacity (often referred to as "bandwidth") problem many systems face today with communications and data links. This technological growth area would especially benefit air missions in prospectively contested environments.

Outline and Scope

The following pages will attempt to link the necessary technology, hardware, architecture, and concept of operations for laser communications in a "mission-level" air setting

by the year 2040. For the sake of this discussion, the tactical environment can be thought of as a mission (or a subset of an air tasking order [ATO]), with multiple formations of various weapons systems, each performing various mission sets. The geographic bounds of the mission can be several hundred miles, perhaps up to 1,000 nautical miles in distance from the farthest separated aircraft. The following discussion stops short of the opportunities and challenges of connecting the "mission" to a centralized control facility or organization such as a CAOC, nor does it address weapons terminal guidance. Furthermore, it does not address delve too deeply into technical details of capabilities or system requirements, but rather focuses on the general capabilities, concepts of operations, and likely benefits.

This discussion on future communications capabilities and requirements assumes that US satellite capabilities will be significantly degraded or even neutralized, through kinetic or other means. Should satellites still be operating and supporting the force, the communications problems become easier, but the current and projected anti-satellite threats appear capable and reliable.[2] It would be difficult to argue against the broad claim that the US military has propped itself upon GPS capability, presenting a critical vulnerability for potential adversaries to attack through various means. From a "worst case scenario" perspective, then, the US and allies' GPS constellations and satellite communications (SATCOM) assets are assumed to be inoperative for this discussion, lest they be relied upon to a fault in the decades ahead.

Lastly, the entirety of this paper is unclassified, which inherently limits access and discussions of the full gamut of technological demonstrations, programs, and future planning. While this certainly limits some of the technical details, it should not impede the conceptual messaging and advocacy for FSO LC technology and its adoption into current and future platforms and programs.

The Technology

Much like fiber optics communicate by passing information via a coherent light signal over a fiber cable, free space optical lasers pass information via "light" through the air, or "free space". A laser transmitter pulses light on and off very quickly and with various amplitudes of power, essentially creating a series of "0s" and "1s" that aggregate into a signal for the receiver. In contrast, RF transmissions modulate a wave's frequency and/or amplitude to create the characteristics of a signal, carrying the information. One defining characteristic, which has already been alluded to, is that lasers do not propagate a broad wave like most RF transmitters (either omnidirectional or at least hemispheric). Lasers transmit on narrowly focused beams directly to the receiver, maximizing the potential receptivity of the signal and minimizing the chance of interception by unintended receivers.

The other dominant defining characteristic of FSO communications is the data rate capacity. As a reference point, radio frequency transmissions average a data rate of 45 megabytes per second (MB/s). ITT Exelis, a defense contractor, has demonstrated successful FSO air-to-air connections at a data rate of up to 3 GB/s over a distance of 80 miles. General Atomics Aeronautical Systems Inc., which is also developing air-to-air FSO link technologies, hypothesizes that rates of 20 GB/s are possible.[3]

The effective range of FSO transmissions depends on a series of variables—wavelength, power, atmospheric attenuation (based on transmitter and receiver locations and line-of-sight), aperture designs, angle of incidence at arrival, etc.—but recent technological demonstrations reveal promising prospects. In October 2013, the Massachusetts Institute of Technology (MIT) Lincoln Labs transmitted data from the moon back to Earth (239,000 miles) on a laser aboard the National Aeronautics and Space Administration (NASA) Lunar Laser Communications

Demonstration (LLCD) at a rate of 622 megabits per second (Mb/s).[4] Setting an even further horizon, NASA is proposing an FSO transmitter on the Mars Reconnaissance Orbiter that could transmit images back to Earth (140 million miles) at a data rate of 100 MB/s.[5]

Given the focused and directed nature of FSO LC, the ability to align the transmitter with the receiver—effectively to "aim" the laser aperture—is the crux of the technology, especially in a highly mobile, dynamic environment of air-to-air participants. Besides the main laser transmitter and receiver diodes, each participant in a bi-directional laser communications link must be able to locate and track the other in order to maintain an adequately tight line-of-sight for subsequent transmissions. A laser scanning array (LSA) has demonstrated the ability to locate and track other FSO LC participants to aid in aligning the respective transmitters and receivers. In 2009, a pair of Cornell University engineering students rigged a laser aperture to a motor-controlled servo to automatically scan for a laser receiver across a room, and then transmit a simple audio signal from the transmitter to the receiver. The experiment (which cost $61.04 in its entirety) successfully passed a precisely representative audio signal, representing a proof-of-concept for scanning and locating a recipient.[6] ITT Exelis's air-to-air demonstration proved a leap in the maturation of this capability, providing an encouraging trajectory. Clearly, then, the challenges of locating and maintaining "track" of a transmitter and receiver can be overcome. There are other ways of maintaining positional awareness of other aircraft through reference systems and hybrid RF-FSO systems, which will be discussed later.

Hardware

For aircraft that will remain a "safe" distance from air or surface threats, such as command and control (C2) platforms or intelligence, surveillance, and reconnaissance (ISR), a

relatively sizeable aperture will maximize the flexibility, receptivity, and range of FSO LC. For sake of this discussion, these arrays will be labeled Support Aircraft Arrays (SAA). In the near term, a pod or another externally mounted array could be developed for large size support aircraft. As a starting point for the discussion, these SAAs should be able to receive and transmit with 360^{o} coverage in the X-Y plane, and +30^{o} to -90^{o} in the Z-axis. Given the near-sphere of coverage and lack of requirement for low observability (stealth), these SAAs could be hemispheric, or "domes". Since these platforms will be required to receive signals from multiple transmitters in near real time, the SAAs should consist of sufficient receiver diodes to handle the tactical situation.

For aircraft whose mission sets require more survivability considerations (i.e. fighters, bombers, attack, etc), the FSO LC arrays should be blended into the aircraft airframes for low observability and aerodynamics. The missile launch detector (MLD) windows on the F-22[7] and the electro-optical targeting system (EOTS) on the F-35[8] offer two examples of blended systems that permit full 360^{o} coverage while maintaining tactical considerations for low observability and maneuverability. For future platforms, the combat aircraft arrays (CAA) should balance these tactical considerations with the requirement for sufficient communications coverage similar to those outlined above for the SAAs. For combat aircraft, this might imply multiple arrays around the aircraft to enable complete coverage, much like the sector windows around the F-22 for MLD. Similar to the SAAs, the system of CAAs on an aircraft should be capable of receiving multiple signals in near real time, and transmitting to multiple receivers either simultaneously or in near real time.

FSO LC Architecture

Since laser communications require directed energy rather than a relatively omnidirectional radio frequency for conventional HF, VHF, or UHF transmissions, connecting two or more communicators or participants is not as simple as simply tuning up the same frequency or channel. The two questions that need to be answered in developing the FSO LC architecture are 1) how to determine what participants should receive what communication or information, and 2) how to determine where to aim the signals in order to reach the intended recipients. The former question deals primarily with channelization (or "nets" in the conventional datalink vernacular), while the second deals with establishing and maintaining precise location awareness of the coordinated participants.

As an initial architectural recommendation, laser network groups (LNG) should be established similar to Joint Tactical Information Distribution System (JTIDS) Network Participation Groups (NPG). With the LNGs, two main subsets would distinguish between voice communications LNGs and data LNGs, with further subsets to each. For instance, the data LNGs would be divided into mission data (fuel and weapons states, etc.), ISR and targeting data (imagery, video, battle damage assessment, etc.), and C2 data (tasking messages, package flow and assignments, time critical intelligence updates, etc.).

The determination of which aircraft would participate in each LNG would be made in mission planning, with entry to each LNG protected by crypto. The LNG architecture should ensure each element receives the appropriate communications and information to enhance mission execution and flexibility, while ensuring redundancy and resiliency across the communications links. With this in mind, some aircraft may act as a "pass through" node from one participant to another without processing and displaying the information to the nodal, linking

user. In terms of redundancy and resiliency, a hub-and-spoke architecture should be avoided, lest the single point of communications convergence becomes a vulnerability and potential source of mission failure. At the other extreme, a complete "web" architecture wherein each aircraft is linked to every other aircraft presents technical challenges due to transmitter and receiver limitations, processing power, and the all-encompassing problems of bandwidth. The ideal architecture likely resides somewhere between the two extremes, balancing redundancy and flexibility with technical constraints.

With a robust "web" of scores of aircraft in a given mission, combined with the potential for overwhelming volumes of communication and data and limited processing power, an appropriate algorithm for FSO LC "pathways" between aircraft will be essential. This algorithm should leverage an aircraft's relative awareness of other players, quality of FSO LC to and from each of those players, LNG participation or "subscription", location relative to formation members and other assets, altitude, maneuvering states, etc. Armed with those parameters, the algorithm should determine the best routing for transmitting FSO LC, both voice and data. Perhaps the information transmitted over the laser would be accompanied by bits of data that define the prescribed route, informing each aircraft where they should pass the information.

The type of information shared among LNG participants will be determined by many tactical and mission level variables, largely driven by which platforms would benefit from having each type of information. Without knowing the future platforms, sensors suites, mission sets, and C2 structure, it becomes increasingly difficult to define the parameters for LC information sharing. One can conceive of a series of concentric circles in which less and less information is passed to each subsequent ring—aircraft would pass more information within its formation than it would pass to other like formations, and it would pass even less to other

platforms. In the context of today's platforms and traditional missions sets, a formation of F-22s would share a wide array of information among a four-ship: precise location and flight parameters, fuel and weapons states, air-to-air and air-to-ground track and targeting information, sensor suite data, and synthetic aperture radar (SAR) maps. Multiple F-22 formations would share some of those information sets, but not all. Similarly, each formation of F-22s would pass targeting and sensor suite data to other combat aircraft within a certain radius, but not necessarily other information such as weapons and fuel states. The driving factors in determining the bounds of what information is shared across which LNGs should be 1) what information would benefit other LNG participants by increasing situational awareness and tightening decision cycles, and 2) mitigating the risk of oversaturating the aircrew with extraneous information.

The other core question in the FSO LC architecture is whether the information is pushed or pulled—that is, whether each aircraft automatically passes the information forward to other members of the LNG or whether participants would request the information from others and wait for a response. Perhaps it can have elements of both, where the inner concentric circles would operate best with a "push" system, with outer rings and certain types of information operating under "pull" algorithms, much like an Air-to-Air Interrogator (AAI) system. Such delineation could also mitigate information overload scenarios. Rather than pass every piece of information from an F-22 to a B-2, the bomber pilot can "interrogate" or "pull" a specific piece of information if and when desired, such as a synthetic aperture radar (SAR) map of a target area.

Concepts of Operations

The issue of establishing and maintaining precise locational awareness of friendly aircraft in a given mission presents a crucial link in both the technology and the concept of operations for

laser communications. Currently, most military aircraft maintain their own positional awareness with a combination of inertial navigation units (INU) and global positioning system (GPS), mostly the latter. They also maintain relative positional awareness of other friendly aircraft through data link architecture, wherein each participant provides its location by way of GPS as well. Given the anti-satellite capabilities today and the projection of further developments, relying on GPS for situational awareness and as a crucial link in a communications system would present a tactical vulnerability.

There are two primary methods, however, that aircraft can use to maintain precise location and relative positional situational awareness in order to maintain directed communications links: a GPS-type replacement and/or a scan for and locate friendly participants.

Without GPS satellites to provide precise "triangulation" of one's position in relation to the XY plane (latitude and longitude) and elevation above the spheroid of the earth, another system needs to provide similar assistance. Rather than a network of high velocity medium earth orbit (MEO) stations, a surface-based reference station (SRS) at a stable, known location could provide aircraft with positional awareness either through an RF signal or FSO. Surface-based systems carry the inherent limitation of line-of-sight (LOS) for FSO and range for both RF and FSO, but with modest advances in complementary technologies these limitations can be overcome. It would be unrealistic to assume each aircraft in a combat mission would be able to maintain LOS to a surface-based station given the curvature of the earth and the attenuation limitations of the lower segments of the earth's atmosphere, especially below 10,000 feet mean sea level (MSL).

INU and clock technology are advancing, and given 25 years to mature those technologies even further, it is likely that aircraft will be able to hold a very precise fix on their

location and timing for hours or even days after their last ground reference update. Once an aircraft establishes precise locational awareness on the ground via a ground reference station (perhaps located at each airfield), enhanced by updates through the SRS while in flight (and within a reasonable range of the SRS), the aircraft will be able to maintain locational awareness for longer durations. With a 25 year horizon for technological development, it seems realistic that combat aircraft will be able to maintain a tight enough fix on location and timing for a wide array of weapons employment scenarios.

Once an aircraft is established in an LNG, it could also receive precise location updates through other participants with more recent SRS updates. After an aircraft has flown beyond LOS from a SRS for several hours, its location and timing could be refined by calibrating with other airborne assets with more recent (and presumably higher quality or "tighter") location and timing. Specific airborne platforms for this function will be discussed below.

The ability to receive updated locational information, as well as other laser communications and data, relies upon the ability to "find" the friendly participants. This involves establishing LNGs as well as maintaining and reacquiring positional awareness of other aircraft if and when a link is degraded or lost. When the exact LOS from one aircraft to another is lost due to maneuvers, hardware limitations, attenuation, or any other factors, the "lost" participant will need an automatic capability to regain awareness on the other players.

A reliable future FSO LC architecture will likely consist of quantum packets of data transmission and reception, followed by a "lost link," and a subsequent reestablishment of the link and another quantum packet, etc. When a connection is lost between two aircraft in the current datalink architecture, the reconnection is accomplished via RF, which is still a possibility for a FSO LC concept of operations. Rather than rely upon either an RF beacon (interrogation and response) or

an FSO scan pattern to attempt to relocate other aircraft, a hybrid search or scan aperture (RF and laser together) could be employed. This would maximize the speed and likelihood of locating the other participants by leveraging the omnidirectional nature of an RF "beacon", coupled with a wider angle laser (wider than the comm/datalink beam) in a scan pattern for longer range detection and security. Even a single player's response to the RF beacon or detection via the laser scan would reestablish the link between the two aircraft, leading to reintegration with other participants in the LNGs. In this sense, establishing an LC link with a single participant—read "node"—will flip on the light switch of all friendly aircraft locations, much like JTIDS precise participant location and identification (PPLI) in the current datalink infrastructure. Tying into one aircraft that is established in the LNG and is maintaining LC links with other players will reconnect the previously lost aircraft in the "web", or whatever the determined comm/datalink architecture appears to be.

Safety Outlet—Airborne Relay Station

Given the likely technical challenges of precise location, positional awareness of other aircraft, and the reception and processing of voluminous data, an Airborne Relay Station (ARS) acting as a mission assurance or enabling platform would benefit a complex air mission scenario in a contested environment. This ARS would serve many purposes, primarily as a high data rate, high volume data relay between the mission area and C2 nodes in the rear areas. The speed and distance of air combat in a contested environment, coupled with the assumption of satellites being neutralized, presents a unique challenge for communications due to the curvature of the earth and the atmospheric attenuation in the lower altitudes. A high altitude, long endurance ARS would provide much longer range communications into and out of the mission area,

enabling timely decisions, mission flexibility, and robust intelligence collection and protection. Rather than a single hub, a small but redundant formation of ARSs should be deployed for important missions. Depending on the altitude of the ARS tracks and the distance to the closest ground-based C2 node, a string of ARSs might be required to extend the data relay.[9]

More than just a communications and data relay, the ARS can also “forward-pass” geolocation updates to other aircraft to augment and refine the INUs and clocks. In this sense, it increases the benefits of the SRS for updating precise location. Essentially, if the SRS knows where it is, and the ARS knows where it is in relation to the known location of the SRS, it can act as an airborne reference point. This geolocation update becomes a less demanding requirement as INU and clock technologies advance, but would nonetheless provide a refined calibration.

Similarly, when a participant aircraft loses track of others due to maneuvering, distance, attenuation, or other challenges, the ARSs can be found relatively easily and can then reconnect the lost aircraft with the respective LNGs. Since ARS tracks would be relatively predictable, a lost aircraft could automatically begin a laser scan pattern in a known direction and elevation to find the ARS, rather than scanning the entire sky for other participants. For example, if a combat aircraft lost FSO linkage during maneuvering, it could begin a hybrid FSO/RF scan pattern in the last known azimuth (magnetic heading) and elevation (angle relative to the horizon) of the ARS.

Recommendations

Hopefully the discussion above elicits both concern over a key combat vulnerability and hope in the ability of US and allied forces to strengthen the communications architecture and ensure superiority at the high end of war. The picture painted in the preceding pages implies a

series of recommendations for both technological and doctrinal development, some of which will enhance warfighting abilities and redundancies independent of laser communications. The assumption of GPS and communications satellites being neutralized drives the first three recommendations, regardless of the medium over which communications and data travel.

Accelerate INU and Clock Technology: The current reliance of GPS for aircraft PNT and weapons delivery presents a critical vulnerability for combat effectiveness in a contested environment. Should a prospective adversary neutralize the GPS constellation, US (and coalition) assets need the ability to operate effectively without GPS, and the first step to severing that dependence is to develop much tighter INUs and clocks. A requirement for INUs with low enough drift rates to permit long duration missions, without coupling to a GPS signal or using an overfly update feature, would help drive that development. Some recent studies connote a lack of urgency in the commercial industry to develop better performing INUs due to the assumption that GPS is robust and not threatened. This assumption holds water in a steady state peacetime environment, but even with a degraded GPS constellation the commercial transportation and logistics industry could grind to a halt, depending on weather conditions and risk assessments.[10] Similarly, aircraft internal clocks need to enable time synchronization for communications and weapons delivery, so defining the required threshold in a requirement would drive the technology.

Surface Reference Station: The SRS proposed above would augment and enhance the location, navigation, and timing solution in the internally-carried INUs and clocks, adding redundancy to the system and enabling even longer duration missions. Rather than requiring an aircraft to know its precise location (latitude, longitude, and elevation) at a predetermined ground location in order to calibrate its reference system, an SRS would simultaneously “sync” scores of

aircraft on the ground as well as in the air, up to its range limitations. A defense requirement for developing and implementing SRSs would add this critical redundancy and insulation into the existing warfighting capability, furthering insulating forces from the critical vulnerability of the GPS constellation. While the curvature of the earth and atmospheric attenuation limits the range of these SRSs, they would effectively act as a surface-based GPS for the local area. At a minimum, SRSs should be deployed to known contested theaters. Since the function of SRSs is relatively simple—act as a reference point, provide azimuth and range information to aircraft, as well as potentially receive FSO LC—the cost for these units should be relatively reasonable, especially considering the benefit they would provide.

Field Airborne Relay Station: The ARS concept discussed above would provide redundancy to the current air mission architecture, which would improve mission assurance. The ability to send and receive high data rate, high volume, long range FSO LC could be a modular adaptation on the ARS platform as the accompanying technologies develop. In the meantime, the benefits of a high altitude, long endurance, multispectral communications and datalink platform are self-evident. The degree to which a theater or area is contested increases with proximity to forces or interior lines, driving the need for "reach back" in tactical or mission level lines of communication. Regardless of the future command and control structure-- CAOC, "combat cloud", distributed control, or a combination-- the ability to communicate rapidly, with both voice and data, between airborne assets and decision makers will remain a crux for flexibility and responsiveness.

This ARS capability might exist on current platforms and it might be achievable with modifications to current systems. It might be a long winged, lightweight drone or it might be a modern airship. The important parameters are the capacity to pass information and sufficient

altitude to overcome the curvature of the earth and atmospheric attenuation problems. Given the trajectory of defense budgetary constraints and the drive for multirole platforms, the ARS would likely also be a sensor platform for intelligence, surveillance, and reconnaissance (ISR). If that is the case, all the better—the same ARS platform that is collecting ISR would be able to fuse its collections onboard with those of other combat aircraft that are passing FSO data back to the ARS.

Define FSO LC and Hybrid Requirements: While the defense and commercial industries are continuing to test and evaluate FSO LC apertures, a defense requirement for specific type of arrays with defined capabilities would accelerate the process. Specifically, SAA requirements for a relatively large size, omnidirectional aperture, and CAA requirements for smaller, flush-mounted, series of arrays would refine the development process. If Defense leaders believe laser communications is a possible answer to the problems posed above, a requirement for all combat-coded aircraft to be designed and built with modular communications apertures/arrays would at least smooth the transition to FSO LC in the decades ahead. For example, a handful of panels on fighter aircraft around the airframe with room behind them for hardware (similar to the F-22 MLDs) would permit future modifications or upgrades for laser communications apertures.

At the same time, a requirement for a hybrid communications system that leverages both FSO LC and RF would not only bridge the current hardware and architecture to the FSO development, but it would also stand to benefit the security, redundancy, and assurance of air mission communications. The Johns Hopkins University's Applied Physics Laboratory is working on developing this first generation of hybrid technology for military applications. Their work thus far highlights the benefits of establishing the bandwidth and range that FSO LC brings to the table, while maintaining the all-weather capabilities and reliability of RF. Furthermore, a

hybrid communications platform would improve overall network availability and jam resistance, while leveraging size, weight, and power (SWaP) benefits.[11] Their design offers combat communications benefits across a broad spectrum of applications, from ground-to-ground forces, ground-to-air, and air-to-air. Simultaneously, the Air Force Research Laboratories (AFRL) Rome division is focusing its laser communication efforts along the same lines, betting that a hybrid capability is the best way forward for “24/7 seamless connectivity as well as quantum key distribution”.[12]

Conclusion

Much of the US’s military success can be directly attributed to C3 capabilities across all levels of war. From communications within a formation of fighter aircraft, to the critical calls between a C2 platform and a CAOC cell, and the link back to national leadership, one can clearly see the critical linkages in modern information-based warfare. Any time these linkages break down, friction grinds in the gears of the war making capabilities and reduces overall effectiveness. While such friction impedes operations in any type of war, it would be especially detrimental in a large scale conflict with a peer or near peer adversary. The A2/AD, ASAT, and contested and congested problem sets highlight the need to mitigate critical vulnerabilities in US C3 capabilities. FSO LC and hybrid FSO-RF systems offer a seemingly viable patch for existing vulnerabilities, coupled with increased capacity and capabilities, all with the expressed purpose of maintaining a C3 advantage and ensuring the continuance of the American way of war.[13]

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